HARDWARE-ACCELERATED 2D FLOOD MODELLING: A CASE OF TOUS DAM

Final Year Project UG-2018

Submitted By

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This is to certify that the

Final Year Project titled

“Hardware-Accelerated 2D Flood Modelling: A Case Of Tous Dam”

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In the name of Allah, the most Beneficent and the most Merciful as well as due salutations upon Prophet Muhammad (P.B.U.H).

Firstly, we show the utmost gratitude to Almighty Allah who bestowed upon us the knowledge and the ability to undertake this project; without Whose say we could not have completed it diligently.

We acknowledge the years of hard work, dedication and commitment by our parents and teachers that has enabled us to come this far in life and achieve whatever we have achieved today.

DEDICATION

To our families, friends and teachers.

ABSTRACT

Floods are one of the most catastrophic natural hazards, causing huge losses to lives and infrastructure every year. Floods cause by dam breaks and other damage to critical infrastructure are especially dangerous as they have the potential to cause very high magnitude disasters whose effects may not always be local. Effective flood control and risk management are key components of flood response and mitigation. To this end, flood zoning and hazard maps are prepared from flood simulations based on 1D, 2D and 1D-2D coupled models. In this project, the freeware hydraulic simulation tool BASEMENT was used on a catchment in the Jucar River basin, downstream of Tous Dam. The area under study is around 7.5 sq km and meshes of several granularities are employed. The meshes were prepared from the DTM supplied by CEDEX, the Spanish civil engineering research agency. The inflow data and ground truth data were also obtained from CEDEX. The models were calibrated to accurately capture the flow conditions and ensure consistency. A variety of meshes were prepared to assess the effect of mesh complexity on computational time. The multi-core acceleration was done via two configurations, a 4-core and a 2-core setup. The 4-core setup provided a speed up of around 43.6 % as compared to the 2-core configuration with an actual-time saving (ATS) ratio of 1.772. This workflow can be enhanced to incorporate predictive modelling approaches, provided requisite hydrological data, with adequate lead time, and fine topographic data is available.

In this study, we have validated a hardware-accelerated 2D flood model that simulates the flood event caused by the 1982 failure of Tous Dam.

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List of Acronyms

CEDEX	Spanish civil engineering research agency
CFD	Computational Fluid Dynamics
CFL condition	Stability condition for unstable numerical methods
BASEMENT	Basic Simulation Environment
Cumec	Cubic meter per second
DTM	Digital Terrain Model
DEM	Digital Elevation Model
GIS	Geographic Information System
CUDA	Compute Unified Device Architecture
OpenCL	Open Computing Language
OpenMP	Open Multiple Processing
GPGPU	General Purpose Graphic Processing Units
Manning’s n	Roughness coefficient

CHAPTER 1

INTRODUCTION

1.1 General

This chapter describes the background and introduces the project. It addresses the problem statement and describes the objectives of the study.

1.2 Floods and Modelling

Floods are an age-old problem that humanity has had to contend with for millennia. Flooding, caused by dam breaks, excessive rainfall and storm surge, is responsible for fatalities and economic losses every year. Floods are the most frequent types of natural disaster that cause sizeable economic damage. In 2021 alone, flooding accounted for nearly 1/3rd of all losses from natural catastrophes costing the global economy more than $82 billion (Dickie, 2022).

Climate change is expected to increase extreme flooding across all spatial scales (Brunner et al., 2015). Changing precipitation patterns and extreme precipitation is expected to lead to an increase in flash flooding events across the globe. Floods that develop over hours and days over a catchment can be especially destructive and damaging for critical infrastructure. Flood modelling using different numerical techniques and schemes contributes to an improvement in flood mitigation and flood risk assessment. Various 1D and 2D hydraulic models have been developed to simulate flood events but these are computationally intensive. These models can be sped up by employing hardware acceleration. Acceleration techniques employ dedicated hardware, multi-core CPUs, graphics processing units GPUs, code parallelization etc. Computationally efficient arrangements allow for real time flood forecasting that can assist with hazard mitigation and disaster response planning (Ming et al., 2020)

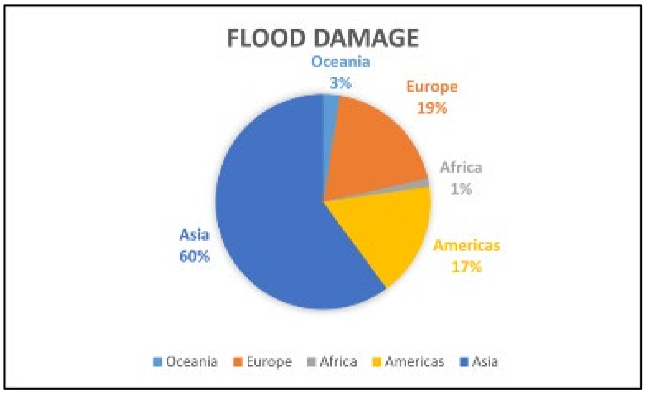


Figure 1: Flood damage as a proportion per area from 1990-2016

1.3 Tous Dam

Construction of the original Tous dam was first started in 1958. However, the discovery of two faults along the riverbed forced engineers to stop construction in 1964 and reevaluate the design. Construction was resumed after 10 year and the first phase was completed in 1978. The peak spillway design capacity of 250,000 cusecs.

Rainfall in Spain is highly variable. The highest average rainfall exceeds 200 mm in north of Spain and 300 mm in south east of Spain. Most rainfall occurs in the month of December and the least rainfall happens in the month of January.

Tous Dam failed only 4 years after the completion of the original structure in 1982, when an intense storm cell delivered 22 inches of precipitation, or about the equivalent of the average total annual rainfall, within a 24-hour period. The dam failure cause grave economic and environmental damage to the tune of hundreds of millions of euros and lead to evacuation of roughly 100,000 people. CEDEX (Center for Studies and Experimentation for the Public Works Ministry, Spain), the Spanish civil engineering research agency conducted a ground survey and asses the flood conditions. They were able to construct a DTM and reliably record flood depths.

Figure 2: Tous Dam after the events of 20th October 1982

Figure 3 Pictures depicting the flood marks and resulting inundation after dam failure in the town of Sumacárcel

1.4 Problem Statement

Developing and performing a hardware-accelerated validation run encapsulating the failure of Tous Dam and the subsequent inundation of downstream localities.

1.5 Objectives of the Study

This project has the following objectives:

1. To simulate the 1982 flood using BASEMENT by developing a calibrated 2D model
2. Accelerate the 2D model
3. Validate the model by comparing with CEDEX data

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter covers the background and literature on flood modelling relevant to the project and also describes the area of interest and the events that lead to dam failure.

2.2 1D and 2D Modelling

The 1D models employed in various use cases today are based on some form of the one-dimensional St. Venant or Shallow Water Equations (SWEs), which in turn can be determined by averaging the Navier-Stokes equations over the cross-section of the channel. Some assumptions made while deriving the 1D SWEs include:

- Hydrostatic pressure distribution (no sharp turns)
- Prismatic channel
- Uniform flow velocity

These 1D equations are solved using numerical methods like the finite element method, finite difference method and finite volume method. Due to an explicit constraint in this technique, the flow in the floodplain is categorized as part of the 1D channel. These models are robust and have been used for several years in the industry. They are computationally efficient but are subjected to modeling limitations, as these cannot simulate flood wave lateral diffusion in the floodplain (Teng et al., 2017). 1D models simulate flows only in the longitudinal direction such as water flows in rivers whereas 2D models are also able to simulate flows in flood plains so can be effectively used for dam break flood events and urban flood inundations (Zischg et al., 2018).

2D models are based on the 2D SWEs obtained by integrating the Navier-Stokes over the flow depth. 2D models are much better able to handle sharp variations in the water surface profile as compared to 1D models. These models, however, are computationally intensive and may take several hours to days to run depending on the complexity of the domain. Although very robust and accurate, the utility of 2D models can be increased if they are computationally sped up to a timescale where decision making on the basis of their results is feasible.

1D hydrodynamic flood modeling assumes that the length of the stream is greater than its depth. For creating a 2D hydrodynamic model, a very detailed topography is required that describes the and flow features of the floodplain. Water level and discharge are totally dependent on an accurate representation of the floodplain. 2D analysis is more complex and thus require more time and skill.

A recent advancement in this kind of dimensional modelling is to employ coupled 1D-2D models. These models have the added benefit of reducing computational effort in areas where only longitudinal flows will suffice and provide greater information where inundation is important or there are obstacles in the reach e.g. bridges (Yin et al., 2020). In this technique, the channel is simulated with 1D flow equations whereas water flowing over the banks and onto the floodplain is simulated using 2D equations.

2.3 Acceleration Techniques

Various techniques have been used by the research community to improve the performance of hydraulic models and one popular technique is the parallelization of codes. This involves Open Multiprocessing (Open-MP) for multi-core systems and the use of GPGPUs (general purpose graphics processing units) among other techniques. The basic comparison between a CPU and GPU in terms of performance in scientific computing is the number of floating-point calculations (FLOPS), where a GPU can outperform a CPU. GPUs were traditionally designed for graphics applications but the advent of APIs and techniques like CUDA (Compute Unified Device Architecture) and OpenCL (Open Computing Language) has opened up GPUs to non-graphics applications. Multiple GPUs from NVIDIA and AMD can functionally be used as coprocessors by software (Castro et al., 2011). BASEMENT supports CUDA-enabled GPUs for acceleration and in the absence of which it only supports multi-core acceleration.

These techniques are incredibly useful because they can dramatically reduce the computational time required for the numerical solution. This has enabled hardware-accelerated coupled hydrological-hydraulic models to be used for predictive modelling (Ming et al., 2020). This application of acceleration is a particularly exciting area of research as it makes it possible to model and predict flood inundation for on demand use cases. This is an emerging need as precipitation patterns change and the nature of natural hazards and their effect on critical infrastructure evolves. As more commercial and open source packages support acceleration, it is expected that hardware-acceleration will become a standard practice when running flood models.

2.4 Tous Dam

Tous Dam was originally constructed in Valencia on the eastern coast of Spain in 1978. It is the last flood control structure in the Jucar River Basin, a watershed that covers about 22,000 sq km. The embankment was initially constructed to be 230 ft tall. The dam was upstream of the town of Sumacárcel, a small settlement in Valencia.

The original structure had a clay core with rockfill shells. The structure was supported on concrete abutments. Its spillway, controlled by three radial gates, was designed for a 500-year return period flow and a peak design discharge of 250,000 cusecs.

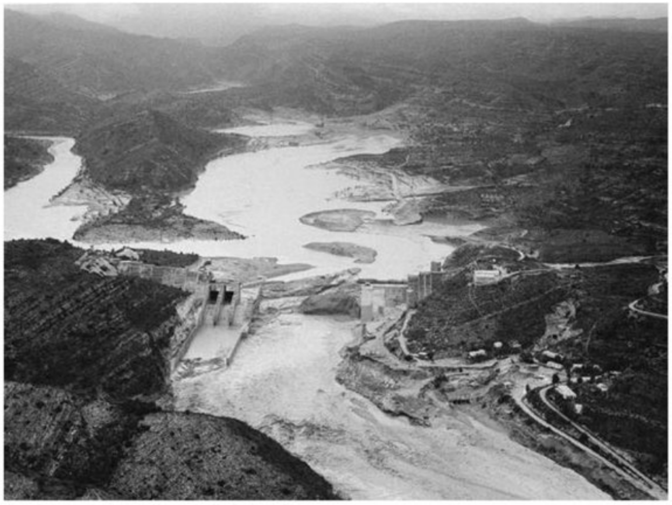


Figure 4: Tous Dam after failure

On 19th October 1982, Valencia experienced an intense precipitation event with 22 inches of rainfall in 24-hr period. Inflows to reservoir were estimated to be 350,000 cusecs. Power to the electrical grid was lost in the early stages of the storm, rendering the spillway gates inoperable. This caused the free board to be quickly filled with water ultimately rising approximately 3 ft above the dam crest. Downstream erosion took away the core and rockfill and the spillway structure collapsed by the next morning. This failure led to more than two dozen fatalities and millions of dollars in damage. The dam was upstream of the town of Sumacárcel and subsequent flooding swept over the town.

The main cause of dam failure was the high intensity rainfall and electric power cutoff due to which the spillway gates are unable to be opened (Garcia et al., 2015). This failure has also been attributed to the lack of effective risk communication between authorities (Serra-Llobet et al., 2013). This incident was the dawn of a new era of risk management in Spain, notable among which are land use planning and changes in the risk communication structure.

Subsequent modelling FLOW-R2D has provided results consistent with ground reports from that time (Bellos et al., 2015). The ground truth data corresponds with the numerical results of the simulation.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter covers the methodology and workflow used to perform simulations, ranging from data acquisition to model inputs and simulation execution and validation. The data sources were provided by CEDEX, the Spanish civil engineering research agency.

3.2 Workflow

BASEMENT is a freeware simulation tool for hydro- and morpho-dynamic modelling, maintained and distributed by ETH Zurich. It can be used to perform the following:

- Simulation of flows under steady and unsteady conditions in a channel as well as in the floodplains
- Sediment transport simulation which includes both bed load and suspended load under steady and unsteady conditions in a channel.
- Simulation the erosion and deposition of bed

The simulation process is built upon three fundamental components: preprocessing, numerical solution and postprocessing. To ensure consistent and accurate results, it is critical that the data being provided to the model are accurate, otherwise the entire exercise becomes an instance of *garbage in, garbage out.* To this end, the data provided by CEDEX were first checked for consistency. The preprocessing involves vetting the terrain and hydrological data. This is necessary to produce a good quality mesh. Preprocessing involves preparing the mesh from the available elevation data which is typically a raster DEM. This step includes the creation of a quality mesh and a computational mesh. Our workflow utilized the raster DTM provided by CEDEX and we created two meshes from this input (111k cells and 86k cells). Special regions in the mesh, such as the town of Sumacárcel, were provided specific input characteristics. The max cell size for the fine mesh was set to 70 m and the max cell size for the coarse mesh was set to 85 m. After the inputs are prepared, they are fed into the mode which after the numerical solution produces four major outputs:

- **Flow velocity magnitudes**
- **Water surface elevations**
- **Water depths**
- **Nodestring discharge**

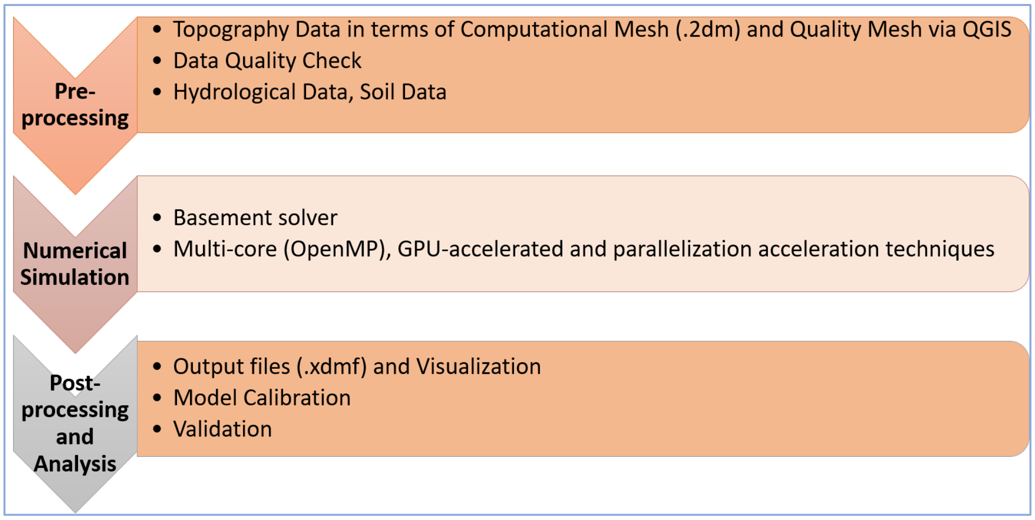


Figure 5: Workflow for simulation

3.3 Preprocessing

This stage involves extensive work within QGIS to prepare the computational domain. The terrain data is loaded, and break lines and nodes are marked. Material IDs are assigned, and regions are defined. This step allows different properties (slope, Manning's roughness, etc.) to be set for each distinct region. The total mesh area, for all resolutions, is around 7.5 sq km

Breaklines:

Breaklines enable quality meshing by preventing the meshing of elements over them during the meshing process. They allow us to delineate the limits of the quality mesh as well as relevant regions like buildings or zones of local mesh refinement. These regions are characterized by marker points (*Regiondefs*) that allow the user to divide the computational mesh into areas of common features for the numerical simulation, e.g setting different initial friction values or definition of an external source over a specific region of the mesh.

Input Data:

The hydrology of the domain can be specified at boundary conditions in the case of water fluxes or over a defined region of the computational mesh if an external source (mass) like rainfall, local source or sink is considered. The water flux can be implemented as a discharge (m3/s), h-q relation or as water surface elevation and the external source can be implemented as discharge or as rainfall precipitation (mm/h).

The hydrological data is inputted as time series data file. The simulation module will then interpolate the desired values to the actual computational time. The source data is either defined as constant or in a time series.

Initial hydraulic conditions can be defined as dry or defined by setting the values of the water surface elevation (*WSE*).

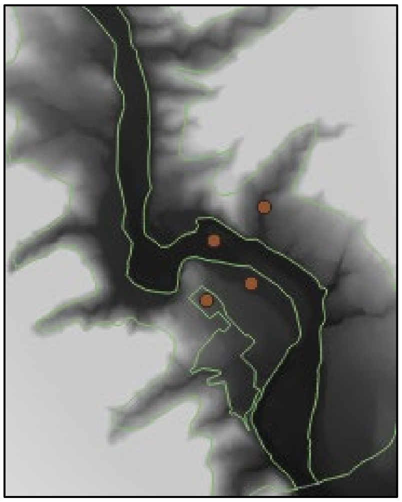
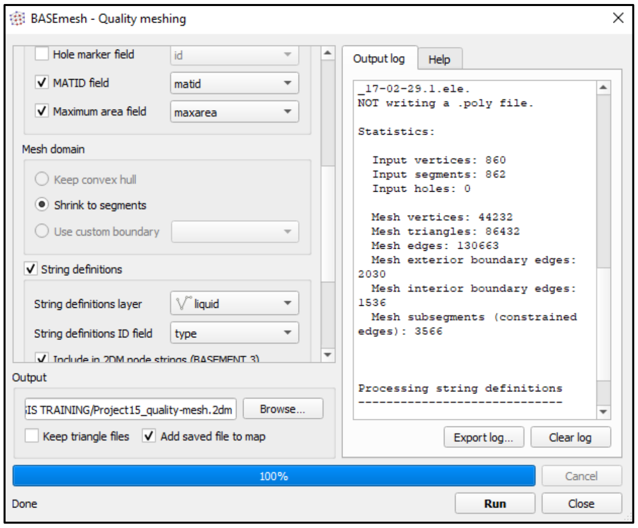


Figure 6: Break line and region

The quality mesh is first created, and the computational mesh is then interpolated.



BASEmesh - Quality meshing

☐ Hole marker field: id

☑ MATID field: matid

☑ Maximum area field: maxarea

Mesh domain

○ Keep convex hull

● Shrink to segments

○ Use custom boundary

☑ String definitions

String definitions layer: liquid

String definitions ID field: type

☑ Include in 2DM node strings (BASEMENT 3)

Output

IS TRAINING/Project15_quality-mesh.2dm

☐ Keep triangle files ☑ Add saved file to map

```
_17-02-29.1.ele.
NOT writing a .poly file.

Statistics:

  Input vertices: 860
  Input segments: 862
  Input holes: 0

  Mesh vertices: 44232
  Mesh triangles: 86432
  Mesh edges: 130663
  Mesh exterior boundary edges:
2030
  Mesh interior boundary edges:
1536
  Mesh subsegments (constrained
edges): 3566

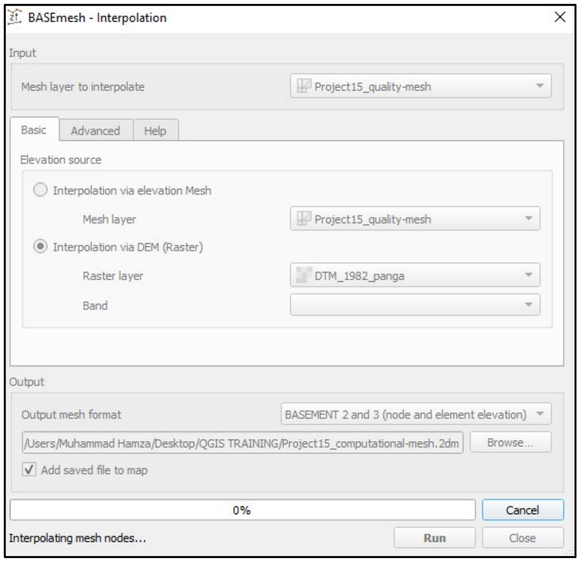


Processing string definitions
------------------------------
```

100%

Done

Figure 8: Quality Mesh



BASEmesh - Interpolation

Input

Mesh layer to interpolate: Project15_quality-mesh

Elevation source

○ Interpolation via elevation Mesh

Mesh layer: Project15_quality-mesh

● Interpolation via DEM (Raster)

Raster layer: DTM_1982_panga

Band:

Output

Output mesh format: BASEMENT 2 and 3 (node and element elevation)

/Users/Muhammad Hamza/Desktop/QGIS TRAINING/Project15_computational-mesh.2dm

☑ Add saved file to map

0%

Interpolating mesh nodes...

Figure 7: Computational Mesh

The mesh is then prepared into the .2dm file and the mesh is smoothed to allow for a continuous coverage. The '.2dm' file is now ready to be supplied to BASEMENT.

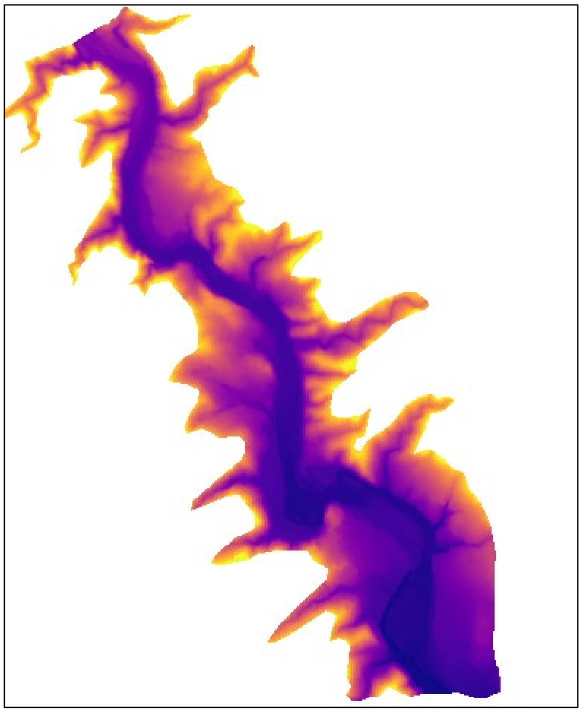


Figure 9: 86k cell mesh of study area

3.4 Processing in BASEMENT

After the hydrological data and mesh have been prepared, they are loaded into BASEMENT and the boundary conditions and other parameters must be defined. These include upstream and downstream slope, initial conditions, CFL value, friction values, among other inputs.

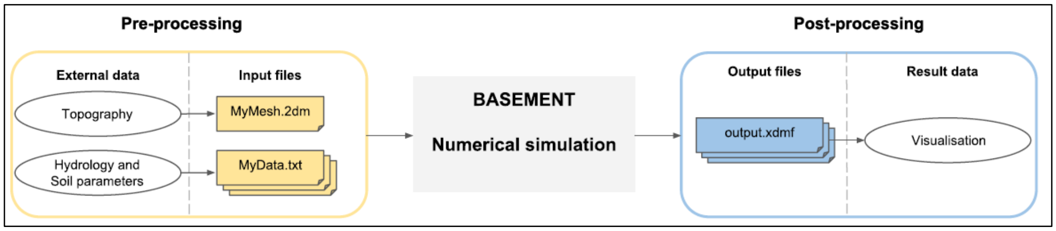
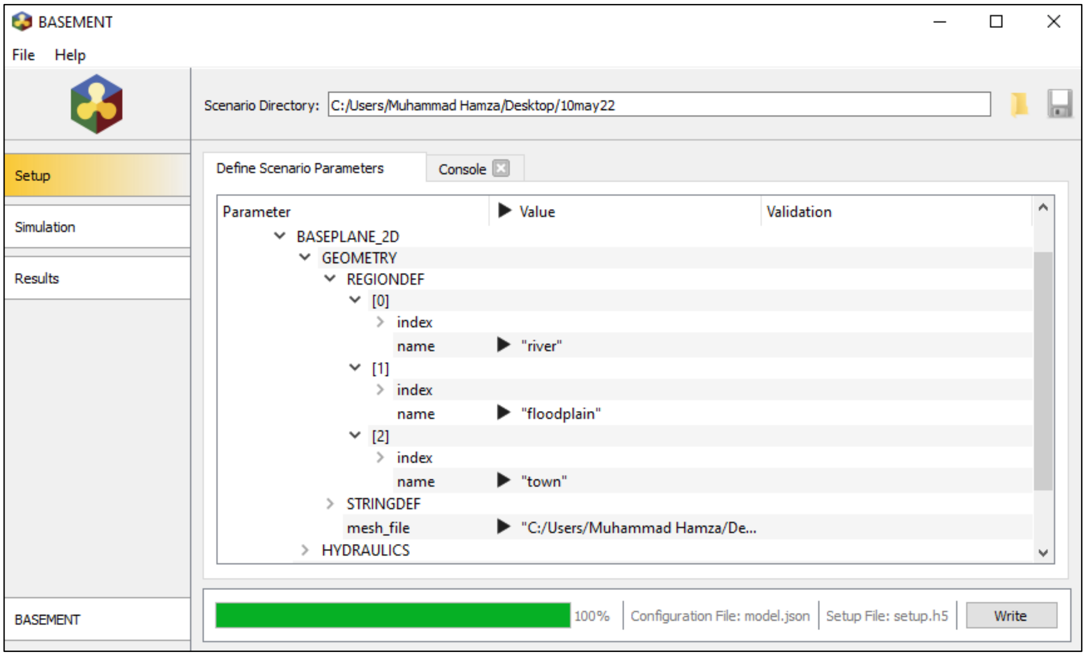


Figure 10: Stages

After the hydrological data and mesh have been prepared, they are loaded into BASEMENT and the boundary conditions and other parameters must be defined. These include upstream and downstream slope, initial conditions, CFL value, friction values, among other inputs.



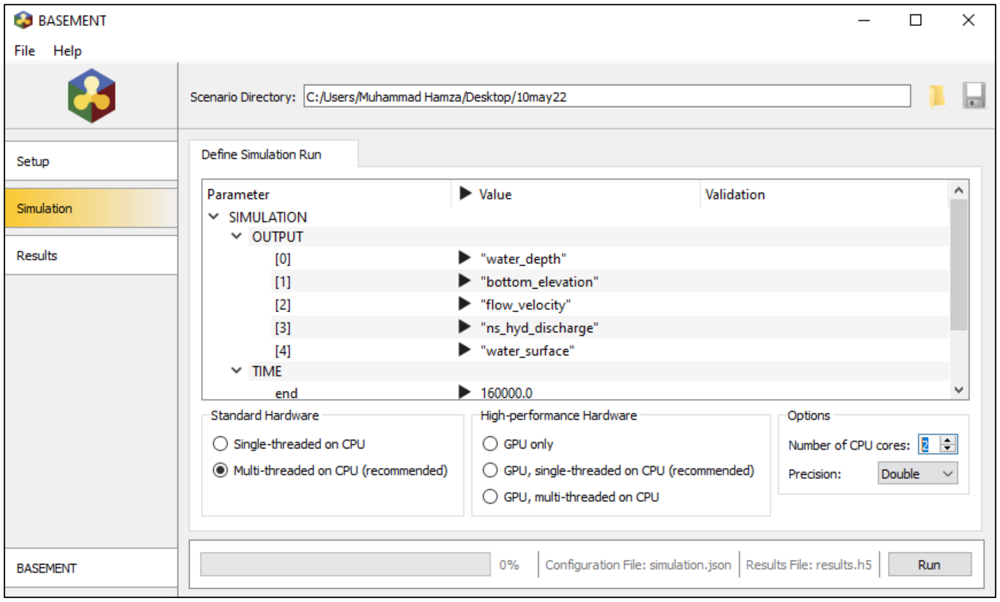
Scenario Directory: C:/Users/Muhammad Hamza/Desktop/10may22

Parameter	Value	Validation
BASEPLANE_2D		
GEOMETRY		
REGIONDEF		
[0]		
index		
name	"river"	
[1]		
index		
name	"floodplain"	
[2]		
index		
name	"town"	
STRINGDEF		
mesh_file	"C:/Users/Muhammad Hamza/De...	
HYDRAULICS		

100% | Configuration File: model.json | Setup File: setup.h5

Figure 11: BASEMENT setup

The simulation time step is set and the simulation is started.



Scenario Directory: C:/Users/Muhammad Hamza/Desktop/10may22

Parameter	Value	Validation
SIMULATION		
OUTPUT		
[0]	"water_depth"	
[1]	"bottom_elevation"	
[2]	"flow_velocity"	
[3]	"ns_hyd_discharge"	
[4]	"water_surface"	
TIME		
end	160000.0	

Standard Hardware
○ Single-threaded on CPU
● Multi-threaded on CPU (recommended)

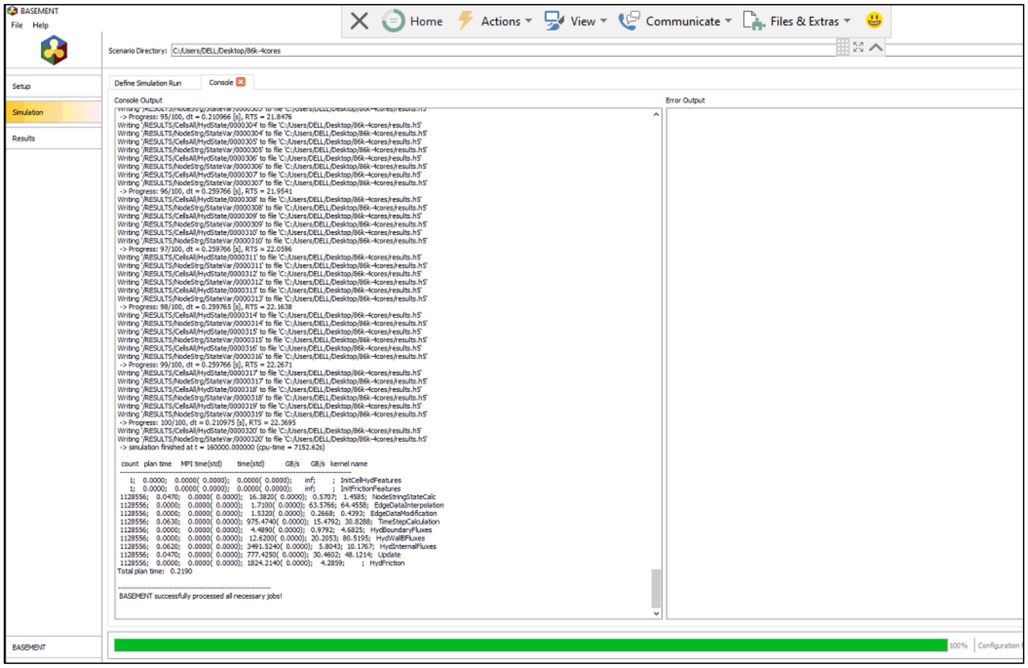
High-performance Hardware
○ GPU only
○ GPU, single-threaded on CPU (recommended)
○ GPU, multi-threaded on CPU

Options
Number of CPU cores: 2
Precision: Double

0% | Configuration File: simulation.json | Results File: results.h5

Figure 12: BASEMENT simulation run parameters

After the simulation has successfully completed, the results can be exported out of BASEMENT and further processed for rendering and visualizations.



Scenario Directory: C:/Users/DELL/Desktop/86k-4cores

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Writing '/RESULTS/NodeStrg/StateVar/0000304' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000305' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000305' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
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Writing '/RESULTS/NodeStrg/StateVar/0000306' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000307' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000307' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
 -> Progress: 96/100, dt = 0.259766 [s], RTS = 21.9541
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Writing '/RESULTS/NodeStrg/StateVar/0000308' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000309' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000309' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000310' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000310' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
 -> Progress: 97/100, dt = 0.259766 [s], RTS = 22.0596
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Writing '/RESULTS/NodeStrg/StateVar/0000311' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000312' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000312' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000313' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000313' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
 -> Progress: 98/100, dt = 0.259765 [s], RTS = 22.1638
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Writing '/RESULTS/NodeStrg/StateVar/0000314' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000315' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000315' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000316' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000316' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
 -> Progress: 99/100, dt = 0.259766 [s], RTS = 22.2671
Writing '/RESULTS/CellsAll/HydState/0000317' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000317' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000318' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000318' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/CellsAll/HydState/0000319' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000319' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
 -> Progress: 100/100, dt = 0.210975 [s], RTS = 22.3695
Writing '/RESULTS/CellsAll/HydState/0000320' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000320' to file 'C:/Users/DELL/Desktop/86k-4cores/results.h5'
 -> simulation finished at t = 160000.000000 (cpu-time = 7152.62s)

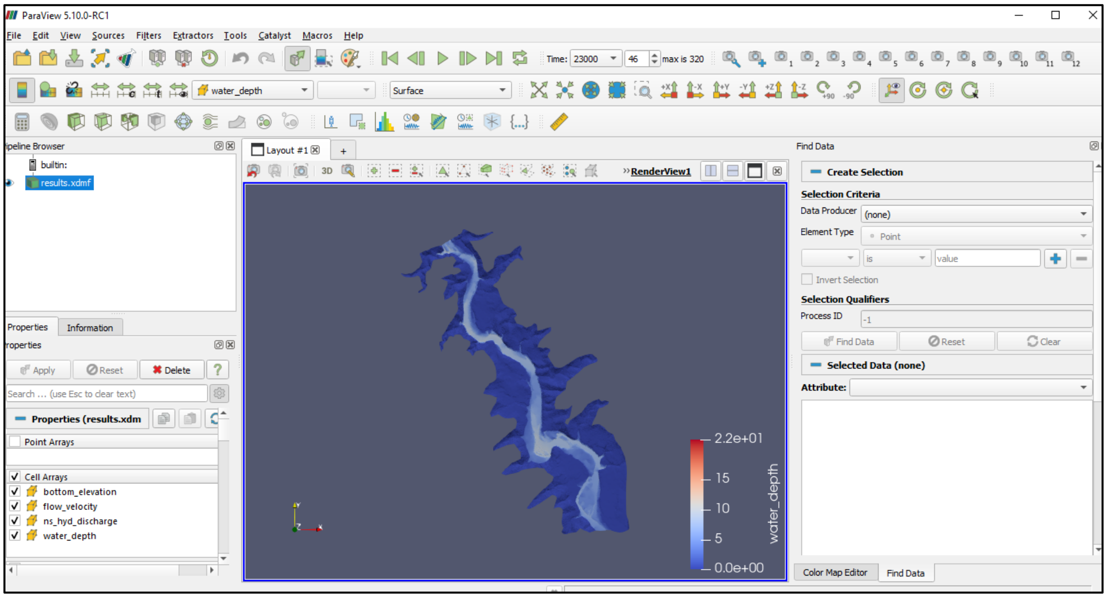
 count  plan time    MPI time(std)       time(std)        GB/s     GB/s   kernel name
 ------------------------------------------------------------------------------------
     1;   0.0000;   0.0000( 0.0000);   0.0000( 0.0000);      inf;        ;  InitCellHydFeatures
     1;   0.0000;   0.0000( 0.0000);   0.0000( 0.0000);      inf;        ;  InitFrictionFeatures
 1128556;   0.0470;   0.0000( 0.0000);   16.3820( 0.0000);   0.5707;   1.4585;  NodeStringStateCalc
 1128556;   0.0000;   0.0000( 0.0000);    1.7100( 0.0000);  63.5766;  64.4558;  EdgeDataInterpolation
 1128556;   0.0000;   0.0000( 0.0000);    1.5320( 0.0000);   0.2668;   0.4393;  EdgeDataModification
 1128556;   0.0630;   0.0000( 0.0000);  975.4740( 0.0000);  15.4792;  30.8288;  TimeStepCalculation
 1128556;   0.0000;   0.0000( 0.0000);    4.4890( 0.0000);   0.9792;   4.6825;  HydBoundaryFluxes
 1128556;   0.0000;   0.0000( 0.0000);   12.6200( 0.0000);  20.2053;  80.5195;  HydWallBFluxes
 1128556;   0.0620;   0.0000( 0.0000); 3491.5240( 0.0000);   5.8043;  10.1767;  HydInternalFluxes
 1128556;   0.0470;   0.0000( 0.0000);  777.4250( 0.0000);  30.4602;  48.1214;  Update
 1128556;   0.0000;   0.0000( 0.0000); 1824.2140( 0.0000);   4.2859;         ;  HydFriction
Total plan time:   0.2190

------------------------------------------------------------
 BASEMENT successfully processed all necessary jobs!
```

Figure 13: Numerical simulation completed

3.5 Postprocessing and Outputs

After the numerical solution is complete, the results are saved into an '.h5' results file which can be exported to the '.xdmf' format. This was then visualized



Time: 23000 | 46 | max is 320

water_depth | Surface

builtin:
results.xdmf

Data Producer: (none)

Process ID: -1

☑ Cell Arrays
☑ bottom_elevation
☑ flow_velocity
☑ ns_hyd_discharge
☑ water_depth

Figure 14: Render in ParaView

with ParaView, an open-source multiple-platform application for interactive, scientific visualization which has a wide breadth of applications across scientific fields from CFD to crystallography.

The 'xdmf reader' reads the input file and renders the output. As the results were rendered in ParaView, they were exported as animations. Visualizations were obtained primarily for water depths, water surface elevations and flow velocity magnitudes. The output files were rendered and also exported as animations. Each timestep of the animation corresponds to about 1.9 hours of the simulated event. The animations have a run time of 21 seconds and in this time, they cover the entire 40 hour flood event. The peak surge is observed around 13.88 hours into the simulation.

3.6 Validation

The simulated results provided water surface elevations and water depths throughout the reach. These depths were compared with CEDEX has also to assess the reliability of the model and asses the validity of the model (see Model and Analysis).

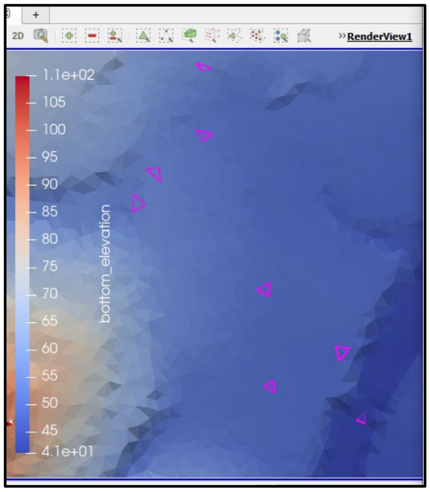


Figure 15: Selecting validation points

CHAPTER 4

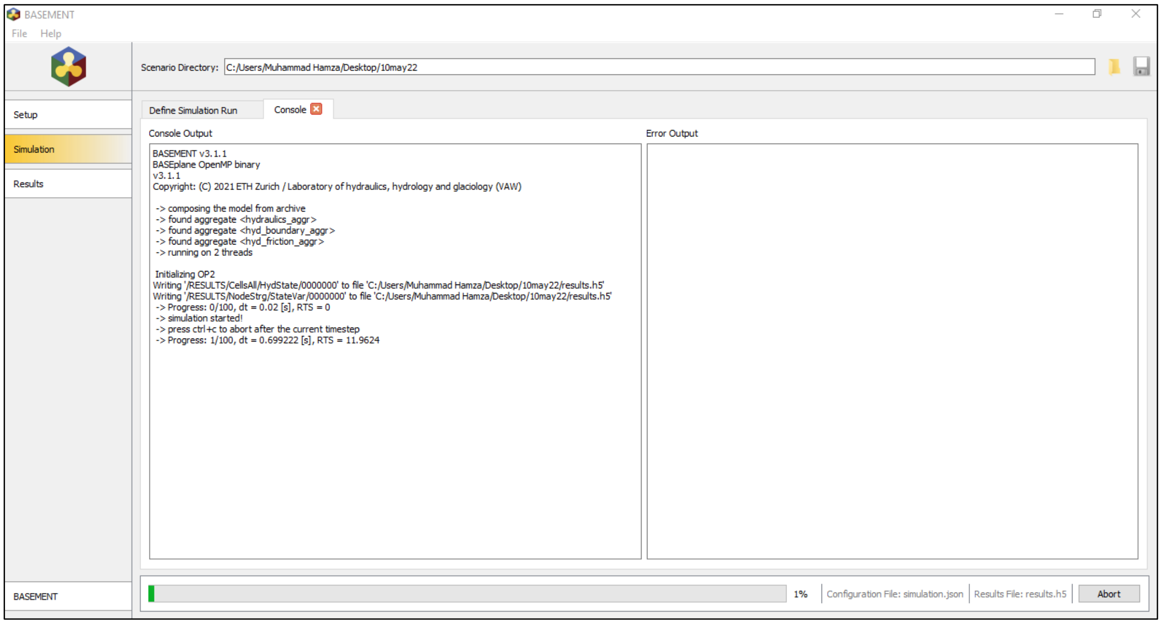
MODEL AND ANALYSIS

4.1 General

This chapter describes the model inputs and analysis after the validation run was performed. It also describes the boundary conditions and other input parameters.

4.2 BASEMENT Workflow

After the preprocessing is complete and the input parameters and boundary conditions have been declared, the simulation time steps are set. This allows us to vary the framerate of the render when the results are exported into ParaView. After this is complete, the simulation can be started. The initial solution step (i.e. 1%) of the simulation is observed to have the highest RTS (real time speedup) across all the runs that were performed. This RTS could be an order of magnitude higher if appropriate acceleration hardware is utilized.



Scenario Directory: C:/Users/Muhammad Hamza/Desktop/10may22

```
BASEMENT v3.1.1
BASEplane OpenMP binary
v3.1.1
Copyright: (C) 2021 ETH Zurich / Laboratory of hydraulics, hydrology and glaciology (VAW)

 -> composing the model from archive
 -> found aggregate <hydraulics_aggr>
 -> found aggregate <hyd_boundary_aggr>
 -> found aggregate <hyd_friction_aggr>
 -> running on 2 threads

 Initializing OP2
Writing '/RESULTS/CellsAll/HydState/0000000' to file 'C:/Users/Muhammad Hamza/Desktop/10may22/results.h5'
Writing '/RESULTS/NodeStrg/StateVar/0000000' to file 'C:/Users/Muhammad Hamza/Desktop/10may22/results.h5'
 -> Progress: 0/100, dt = 0.02 [s], RTS = 0
 -> simulation started!
 -> press ctrl+c to abort after the current timestep
 -> Progress: 1/100, dt = 0.699222 [s], RTS = 11.9624
```

1% | Configuration File: simulation.json | Results File: results.h5

Figure 16: **BASEMENT workflow**

4.3 Acceleration Environment

After an initial feasibility of available acceleration platforms, namely GPU acceleration in an Ubuntu environment and multi-core acceleration in a Windows environment, it was decided to proceed with multi-core acceleration as administrative constraints would not allow for GPU acceleration. The multi-core setup is essentially a comparison of the performance of the 4 core and 2 core configurations. It measures what effect doubling the core count has on the simulation speedup.

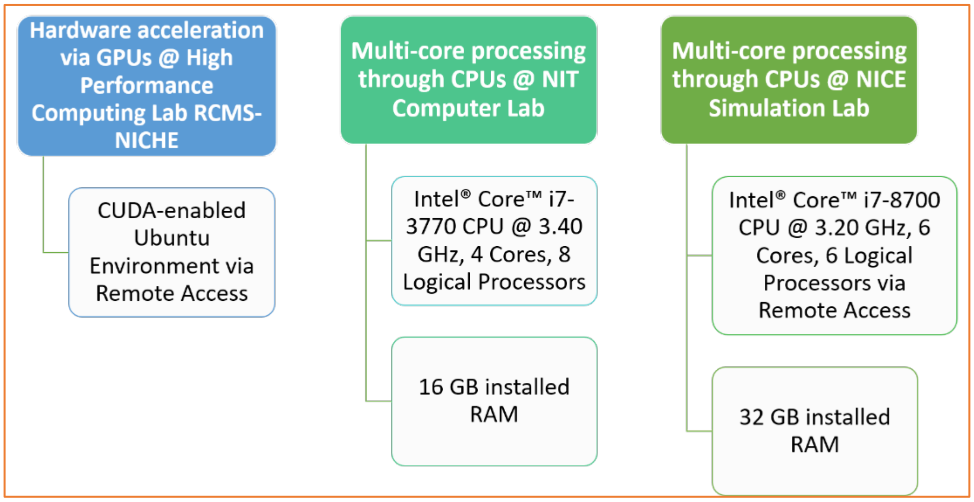


Figure 17: Initial survey of acceleration platforms

4.4 Boundary Conditions and Inputs

The simulations require certain input parameters and boundary conditions that must be explicitly declared as a precondition.

The input hydrograph supplied by CEDEX provides the hydrological input. The simulation models a 40-hour event, with a peak inflow of around 15,000 cumecs.

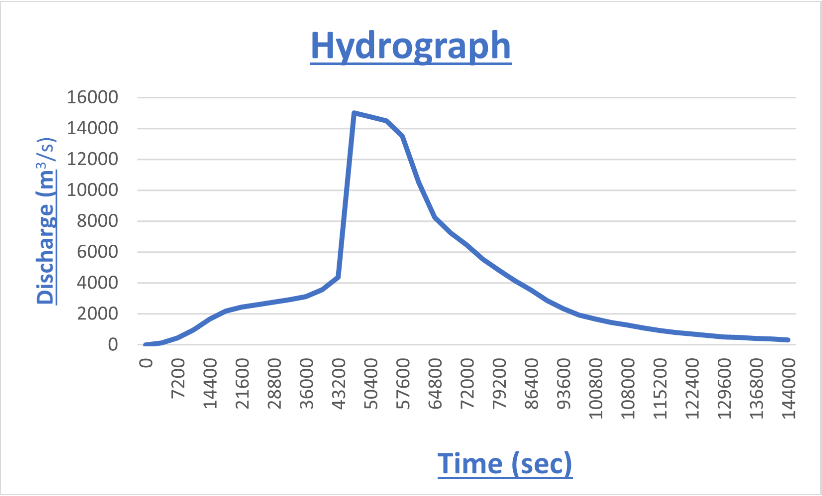


Figure 18: Inflow hydrograph

The boundary conditions set for each run assume a constant inflow and initial dry bed. The CFL was set to 0.90 across all runs.

Boundary Conditions	
Upstream	Uniform_in
Downstream	Uniform_out
Initial Conditions	Dry bed

Figure 19: Boundary conditions

Sr no	Name	Value
1	CFL	0.90
2	Total Run Time	40 hrs

Figure 20: CFL

4.5 Calibration

In totality, the simulation for the dam failure event was run more than a dozen times by varying conditions and input parameters. Some of the meshes used include a 66k, 88k and 96kcell mesh with maximum cell size set to 85, 80 and 75 m. Other than the mesh granularity, one of the most important inputs that the model is most sensitive too is the Manning's coefficient for a region. Varying the roughness coefficient for the town was essential in ensuring that the model reflected reality and accounted for the presences of buildings and paved areas and incorporated their increased roughness. As such, the n value for the town (0.3) was set about one order of magnitude higher than the flood plain (0.06) and main channel (0.04). This calibration was important and ultimately allowed the model to provide consistent results.

Roughness Coefficient			
Manning's n	Main Channel	Flood Plain	Town
	0.04	0.06	0.3

Figure 21: Roughness coefficient for validation

4.6 Validation

The fine mesh (111k) was used to validate the results of the simulation. The CEDEX survey provided flood depths for several ground points around the town of Sumacárcel. Nine of these points were used to validate the simulated water depths. The validation exercise aims to validate the results of the simulation by comparing the simulated depths with the ground truth data collected by the CEDEX survey. The points were chosen in and near the town of Sumacárcel.

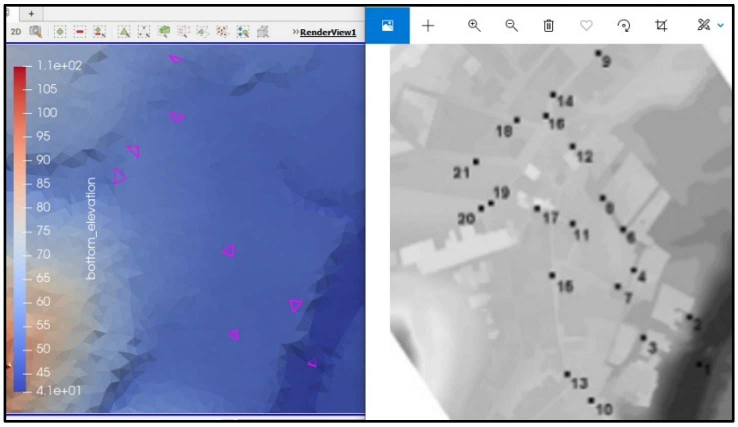


Figure 22: Point selection for validation (simulated depths on the left)

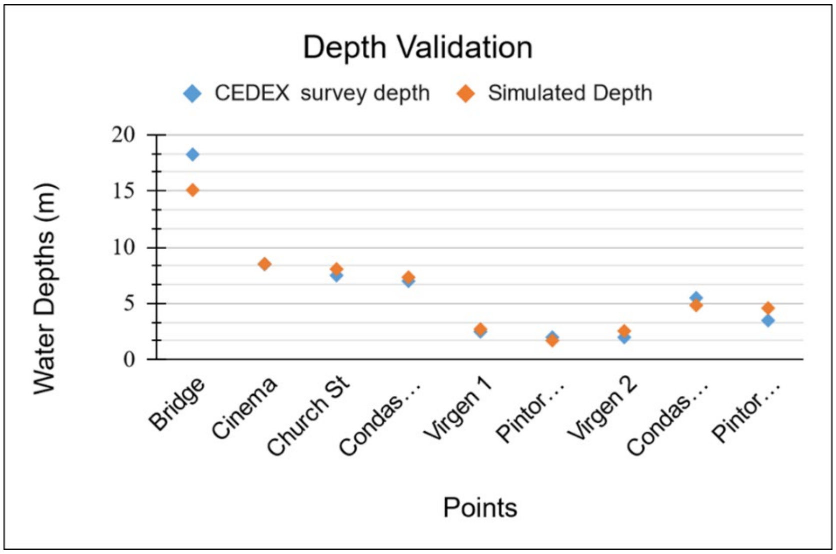


Figure 23: Depth Validation

The fine mesh (111k) was used to validate the results of the simulation. The CEDEX survey provided flood depths for several ground points around the town of Sumacárcel. Nine of these points were used to validate the simulated water depths. The validation exercise aims to validate the results of the simulation by comparing the simulated depths with the ground truth data collected by the CEDEX survey. The maximum average difference between the CEDEX depths and simulated depths is *0.765 m*. Most of the simulated depths agree very closely with the observed depths on the ground with only one point near the bridge where there is a noticeable difference in the simulated and observed depths. This lends credence to the model and validates the simulation.

It is pertinent to mention that the mesh used for validation (111k cells) incorporated the change in surface conditions near the town of Sumacárcel by varying the value of the roughness coefficient (Manning's n) to make the mesh realistic and reflective of the ground conditions during the event.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 General

This chapter covers the results obtained from the hardware-accelerated runs and covers the speed up provided by the acceleration. It also describes some of the nuance in the results (86k-cell mesh and 111k-cell mesh) and discusses how they relate to the ground truth data in terms of the validation of the simulation. The simulation is conducted for 40 hours from the available upstream hydrograph.

5.2 Flood Depths

An important output of any flood modelling exercise is the simulated flood depths. This is especially critical in a predictive modelling framework but also of interest in a validation exercise. As described, the model was run iteratively a number of times to assess the effects of the input parameters. The results presented here are those of the calibrated model and specifically discuss the final two computational meshes used for the validation exercise.

The main surge in flood depths is observed at **13.88 hours** into the simulation with peaks occurring nearing the bridge and other locations near Sumacárcel. A peak flood depth of around **21 m** is modelled upstream of Sumacárcel. Whereas a maximum depth of around 11 m is recorded in the immediate vicinity of Sumacárcel and 18 m near the bridge. The rise in depths lags behind but follows the inflow discharge.

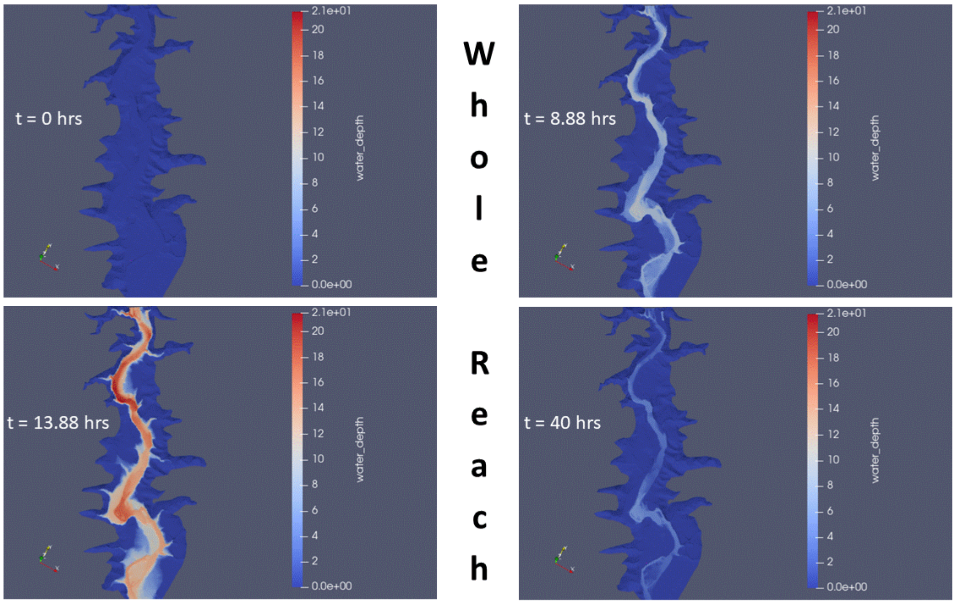


Figure 24: Flood depths for area of interest

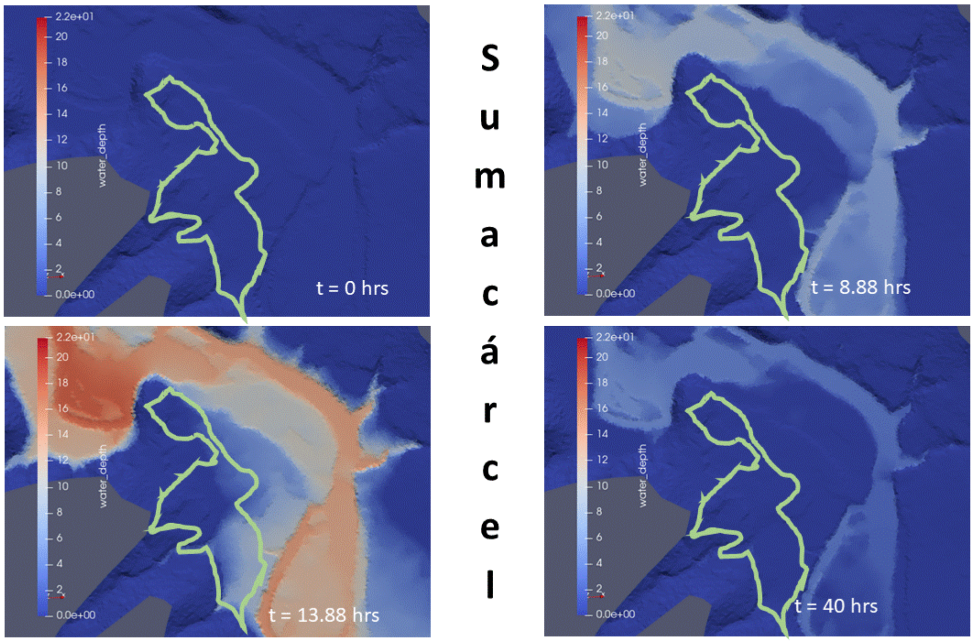


Figure 25: Flood depths for Sumacárcel (outlined)

5.3 Water Surface Elevations

These results describe the variation in water surface elevation as the flood event proceeds and the surge first arrives and recedes. The peak is again observed at around 13.88 hours into the 40-hour simulation. The water surface elevation is greater than the flood depth for all cells as the flood depth is referenced from the bed of the river.

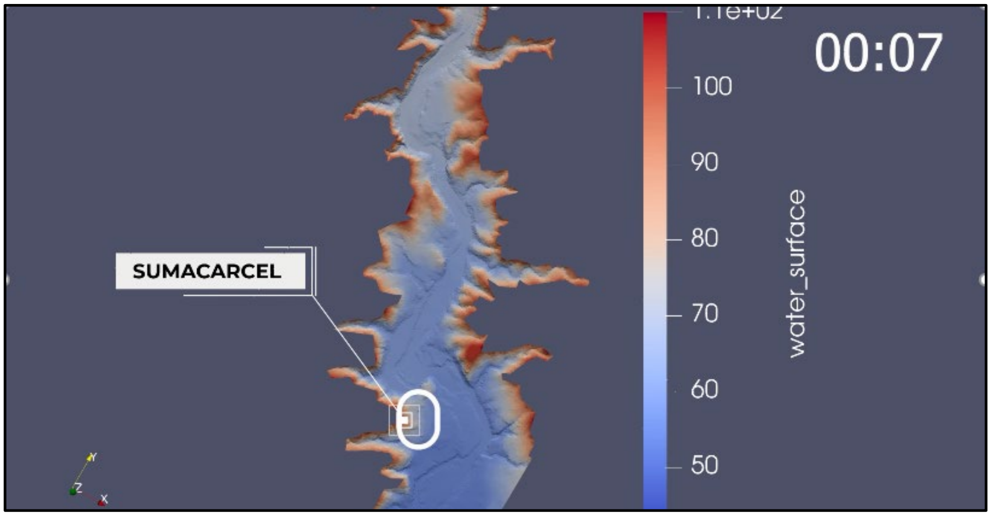


Figure 26: Water surface elevations

5.4 Flow Velocities

The most destructive effects of a flood stem from the high discharge and high-speed surges that often carry debris and uproot property and vehicles. The dam break in 1982 is believed to have caused a peak surge near the town of Sumacárcel at around 13.88 hours post dam failure. There is a concentration of high velocity fields around the meanders of the reach and it along a southern meander where the town of Sumacárcel lies. While no field verification could be sought for this attribute, the modelled velocities are at par with observable flow velocities for comparable floods.

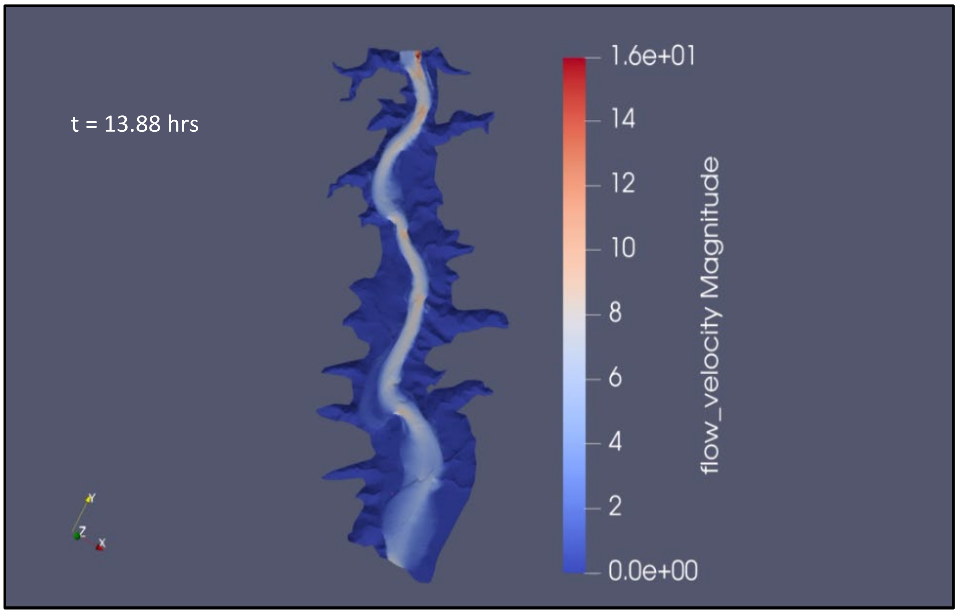
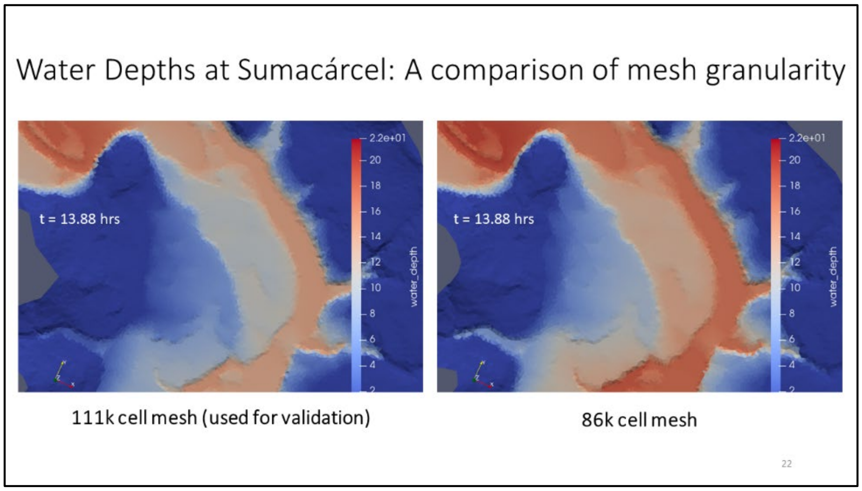


Figure 27: Flow velocities during peak surge at t = 13.88 hours

The most destructive effects of a flood stem from the high discharge and high-speed surges that often carry debris and uproot property and vehicles. The dam break in 1982 is believed to have caused a peak surge near the town of Sumacárcel at around 13.88 hours post dam failure. There is a concentration of high velocity fields around the meanders of the reach and it along a southern meander where the town of Sumacárcel lies. While no field verification could be sought for this attribute, the modelled velocities are at par with observable flow velocities for comparable floods.

5.5 Mesh Granularity

The workflow incorporated simulations run at various mesh granularities, ranging from the coarse 45k-cell mesh to a 111k-cell fine mesh and several cell counts in between. As Figure 25 depicts improving the mesh granularity to encompass more precise domain representation has a noticeable effect on the simulated flood depths. All other parameters held constant; the finer mesh provides more accurate simulated depths as compared to the coarser mesh. The actual depths recorded by CEDEX at this location are consistent with the 111k cell mesh. The coarser mesh simulation overpredicts the water depths, in some cells by over 3 m. For the finer mesh the largest cell size was fixed to 70 m and the triangular elements were interpolated over the better discretized domain.



Water Depths at Sumacárcel: A comparison of mesh granularity

111k cell mesh (used for validation)

86k cell mesh

Figure 28: Comparison of mesh granularity

5.6 Speed Up and Actual Time Saving Ratio

The purpose of utilizing hardware acceleration is to greatly reduce the computational solve time of the simulation. This allows the modeler to get quicker results from the simulation. 2D simulations are computationally intensive and can take days to run, depending on the complexity of the domain. The acceleration makes meaningful predictive runs possible while also speeding up validation runs.

For the final validation run, for which results are reported, this project ultimately utilized a multi-core acceleration environment supported by Intel® Core™ i7-8700 CPUs @ 3.20 GHz with 6 Cores (6 Logical Processors) and 32 GB of installed RAM available at the NICE Simulation Lab. The facility was accessed remotely. Two configurations were used: a 4-core configuration and a 2-core configuration.

Both the coarse and fine mesh were employed for the two configurations and a comparison was done between the run times for the coarse and fine mesh on one configuration and between configurations.

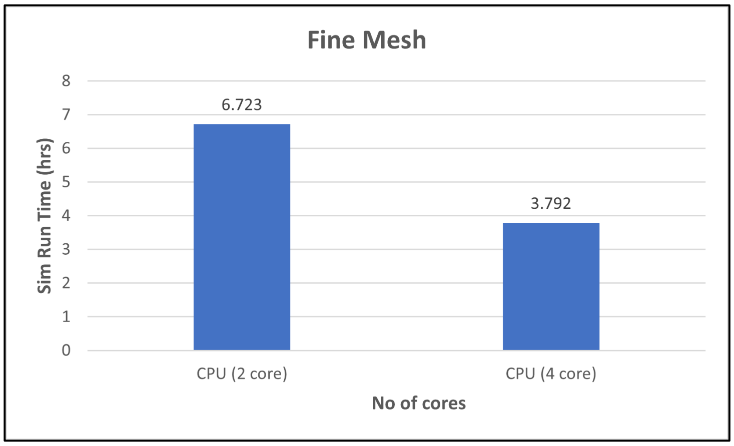


Figure 29: Sim run time for fine mesh

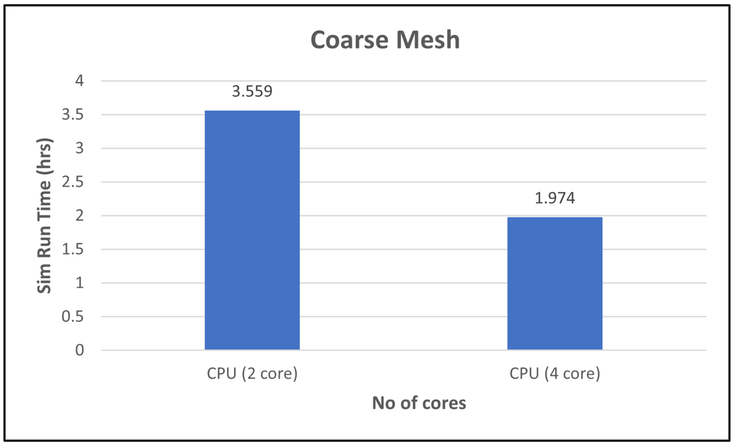


Figure 30: Sim run time for coarse mesh

Mesh	Nodes	Elements	Simulation Time	
			CPU (2 core)	CPU (4 core)
Coarse	56774	86k	3.559 hrs	1.974 hrs
Fine	44715	111k	6.723 hrs	3.792 hrs

These results demonstrate that the coarse mesh required a compute time of 3.559 hours on a 2-core configuration and a compute time of 1.974 hours on a 4-core configuration. Whereas the fine mesh required a compute time of 6.723

hours on the 2-core configuration and 3.792 hours on the 4-core configuration. This provided a speed up of around 43.6 % as compared to the 2-core configuration with an actual-time saving (ATS) ratio of 1.772.

5.7 Applications in Pakistan

This modeling framework is especially useful in preparing for disaster response and planning. The current workflow could be well adjusted to aid in simulating a dam break scenario for several potentially vulnerable dams in Pakistan like Tarbela and Rawal Dams, among others. Models run beforehand aid in preparation of evacuation plans by civil agencies and disaster response forces.

Some of the small dams in Pakistan, like Rawal Dam, will be reaching their design lives by midcentury or have already reached this threshold (Ali, 2012). As such, a formidable response plan should be set in place in the case of any untoward failure. This would be based on the expected inundation caused by a dam failure, with modelling specifically done for several kinds of catastrophic failure. *Inundation extent, expected flood depths, expected water velocities and debris movement* are key parameters to analyze. These results would help decide the extent of the evacuation area and the time required to complete evacuation in addition to the lead time and warning time the surrounding community would have to be given to safely leave the flood zone.

CHAPTER 6

CONCLUSION

6.1 Conclusions

The dam break event and the resulting inundation of downstream localities has been successfully simulated and validated with BASEMENT v3.1.1 and the survey data provided by CEDEX. The validation run, performed on a 7.5 sq km, 111k-cell mesh with a spatial resolution of 10 m, simulated the 40-hour flood event from failure through peak discharge with a compute time of 3.792 hours on a 4-core configuration. This provided a speed up of around **43.6 %** as compared to the 2-core configuration with an actual-time saving (ATS) ratio of **1.772**.

The simulated water depths closely agreed with the ground truth observations with a maximum average difference of 0.765 m in the observed values. The water depths were validated at 9 points where survey data were available. These points are all closely located in the town of Sumacárcel. Several simulated runs have provided consistent results which suggests the numeric solvers are robust.

6.2 Future Considerations and Limitations

The current workflow does not incorporate bed load transport or debris flow which may have occurred as a result of dam failure. While expected sediment discharge may be low, the impact of debris on downstream structures should be evaluated, which is future direction that can be explored.

A comparison between acceleration platforms i.e. CUDA-enabled GPUs and multi-core processing could not be performed due to the unavailability of a specific GPU-enabled environment.

Some variation in water depths is expected due to ponding from a previous precipitation event. This results in some expected deviation of the simulated water depths from the depths recorded by CEDEX.

6.3 Recommendations

Establishing an end-to-end simulation framework would allow efficient processing of precipitation and topography to facilitate both hydrological and hydraulic modelling for on-demand use cases; this requires specific **high-performance hardware** and *granular input data* with a significantly accurate forecast.

These **data constraints** may be resolved at the institutional level through better data sharing between government agencies but must also be addressed for end-users like researchers who wish to use this data. Addressing this gap would allow for the project scope to be significantly increased.

The local availability of better acceleration platforms (e.g. high performing GPUs) would speed up validation runs and allow for meaningful predictive runs, a need which is intensifying in a **rapidly changing climate**. Many dense urban areas would benefit from flood mitigation plans in the event of sudden floods. An accelerated platform allows for flood modelling to be done in near real-time making it possible to affect change on the ground, saving lives and minimizing damage. Pakistan is top among the countries most likely to experience some of the most extreme effects of climate change with an expected increase in extreme precipitation events: investing in predictive modelling approaches today is a commonsense strategy to mitigate damage tomorrow.

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